INTER-TRIAL GAIT VARIABILITY REDUCTION USING CONTINOUS CURVE REGISTRATION

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Abstract-**Timing in peak gait values shifts slightly between gait trials. When gait data are averaged, some of the standard deviation can be associated to this inter-trial variability unless normalization is carried out beforehand. The objective of this study was to determine how continuous curve registration, an alignment technique, can reduce inter-subject variability in gait data without altering the original curve characteristics. Gait data was obtained by means of a four-camera high-speed video system synchronized to a force plate. Fifty-nine gait trials data were collected from twenty young and healthy subjects. Curve registration was applied to hip angular displacement, net moment and power curves generated in the sagittal plane. Following registration, the peak values increased by an average of 1.2% (0.11±0.26°) for angular displacement, and for powers by 11.2% (0.11±0.09 W/kg). First and second derivatives of the unregistered and registered curves did not displayed important differences and harmonic content of the signals was practically unaffected. Continuous curve registration would thus be an appropriate technique for application prior to any statistical analysis using able-bodied gait patterns.**

Keywords: **gait, continuous data, curve registration technique.**

I. INTRODUCTION

Modern video-based systems combined with force plate sensor provide large quantities of kinematic and kinetic gait data. In time, such data often display a sequence of events such as peak, valleys, zero crossing, flat regions, and so forth. Whereas to simplify the analysis and facilitate interpretation of such data, peak values are often used to characterize both able-bodied [1] and pathological [2] gaits.

Gait patterns of able-bodied subjects can be assumed to be reproducible but with some variation in both timing and amplitude [3]. By ignoring such timing variation, information can be lost when trials of several subjects are averaged. This leads to an estimate that does not closely resemble any of the individuals observed curves [4]. This cross mean curves has often less variation during the puberty than any single curve, and the duration of the mean pubertal growth spurt is rather larger than for any individual curve. This problem illustrated in Figure 1, which is the hip sagittal muscle power curves derived from five able-bodied subjects. The peak powers at push-off occurred within a spread of 11% ranging between the 52% and 63% marks of the gait cycle. By averaging these curves, the mean power would be 3.22 W/kg rather than 4.71 W/kg (32% difference) obtained by measuring each individual peaks and then taking their mean value. Similar results can be obtained for the other peaks of these curves. This stresses the importance of data normalization before doing any gait patterns analysis.

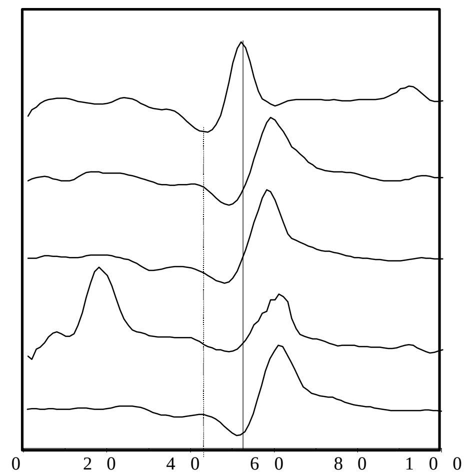

Figure 1. Hip muscle power curves developed in the sagittal plane during a gait cycle for five subjects. The dashed and solid lines are respectively aligned with the beginning and the peak value of the hip power generation at push-off for the subject whose curve is shown at the top.

In engineering, biology, physiology and other fields, curves alignment is normally achieved [5,6,7] by identifying the timing of certain salient features. Curves are usually obtained through marker position detected by a camera system. However, some marker events may be missing from certain curves or timing estimates might be difficult to obtain. Such problems are absent in continuous curve registration [4]. To our knowledge, continuous curve registration has never been used in gait data processing. We hypothesize that this approach could reduce the inter-subjects variability without perturbing the inherent characteristics of the data. It is also possible that it could be applied to various parameters of the gait. To explore these hypotheses, continuous curve registration [4] was applied. It was applied on the hip data, which present greatest inter- and intra-subjects variations [8]. Our main purpose is to study how continuous curve registration can reduce inter-subject gait variability in able-bodied subjects without perturbing the characteristics of the data.

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Abstract

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II. METHODOLOGY

Twenty young healthy adult men participated in this study (age: 25.3±4.1 years, height: 1.77±0.06 m, mass: 80.6±13.8 kg), in which each providing three gait trials.

The procedure of data assessment [9] can be resumed as follows: a rigid body three-segment model, video (90 Hz) and force plate (360 Hz) data were applied to calculate hip angular displacement, muscle moment and power data developed at the hip in the plane of progression. The moment and power values were normalized with respect to body mass. Data were labeled. For example, H3P corresponds to the third hip power burst. The mean stance phase of the right limb of the 20 able-bodied subjects was 60.68% GC.

The continuous registration technique [4] was applied separately on each of the continuous hip sagittal angular displacement, muscle moments and power curves and consisted of two steps. First we estimated a mean function *(s)* by the sample average *c(s).* We then registered each curve $x_i(s)$ to the target function which was this unregistered cross-sectional mean *c(s).* The measure of curve alignment for $x_i(s)$ to *c(s)* was the smallest eigenvalue of the two by two matrix containing squared norms of *c(s)* and *c(s)* in its diagonals and inner products of these two functions in the off-diagonals. This first registration step produced both a shift estimate d_I and nonlinear transformation of time *s* that aligned the curves. Since one of the goals of registration is to produce a better estimate of exactly this mean function *c(s,),* therefore must proceed iteratively. Beginning with unregistered cross-sectional estimated mean, this estimate is updated in the second step by re-estimating it from the registered curves $x_i^*(s)$, and a new iteration is then undertaken using this revised target mean. It has found that the process usually converges very quickly, and practically it has been determined that with reasonable initial estimates, as single iteration is often sufficient [10].

To verify to what extent curve registration modified the peak muscle powers, differences between the unregistered and registered corresponding peaks were determined. The effects of registration on the curve structural characteristics were also evaluated. The root mean square (RMS) difference was calculated to quantify the changes in the shape of the curves. To determine the presence of discontinuities in the unregistered and registered curves, their first and second derivatives were obtained by the central difference technique. A power spectrum analysis was performed to test if the registration technique modified the harmonic content of the muscle power curves. Differences obtained using student t-test at $p<0.05$.

III. RESULTS

Angular displacement, muscle moment and power curves developed at the hip are presented in Figure 2. Mean value of peaks from individual measurements on each curve and from their average curve obtained before and after registration (Table 1). Differences between the individual and the mean values of 5 peaks were significantly reduced after curve registration and 6 of the registered peaks were larger than unregistered average peaks. Following registration, mean peak values for the angular displacement and powers increased respectively by 1.2% and 11.2%, while it decreased for moments by 0.8%. Though the mean changes was small, substantial increases were noted for hip a) H1P; 14.2%, b) H2P; 12.2%, c) H3P; 9.3%).

Table 1: Mean and standard deviation (SD) of peak angular displacement (degrees), muscle moments (Nm/kg) and powers (W/kg) obtained from individual curves (ind.) and from their average curve (ave). Differences are expressed in % for unregistered and registered data.

	Peak	Unregistered Ind. Mean (SD)	Unregistered Ave. Mean (SD)	Unregistered Diff. %	Registered Ave. Mean (SD)	Registered Diff. %	Un/Re Diff. %
Angular displacement	H1	31.67 (9.34)	30.57 (8.93)	-3.6*	31.23 (7.14)	-1.4	2.1
	H2	-28.36 (17.74)	-27.51 (17.92)	-3.1*	-28.19 (17.59)	-0.6*	2.4*
	H3	36.62 (10.51)	35.94 (10.33)	-1.9*	35.71 (10.41)	-2.6*	-0.6
Muscle moment	H1	-0.96 (0.31)	-0.63 (0.34)	34.4*	-0.62 (0.33)	-36.0*	-2.4
	H2	0.69 (0.27)	0.53 (0.35)	-29.2*	0.54 (0.25)	-28.0*	1.0
Muscle power	H1	0.92 (0.86)	0.72 (0.82)	-28.3*	0.84 (0.79)	-10.1	14.2*
	H2	-0.56 (0.85)	-0.77 (0.86)	27.4*	-0.88 (0.78)	36.2*	12.2*
	H3	1.81 (0.99)	1.62 (0.93)	-11.6*	1.79 (0.98)	-1.3	9.3*

Statistically significant differences ($p<0.05$) are indicated by *.

A mean curve was obtained from the individual signals and RMS differences between each individual curve and the mean curve were calculated. Mean and SD of these 60 values are presented in Table 2 for the unregistered and registered data. The RMS values of the registered angular displacement and muscle power curves were smaller than for the unregistered ones. Curve registration decreased the mean RMS values of the data by 56%, 0% and 20% with the greatest reduction for the hip angular displacement.

First and 2nd derivatives of the data were used to observe changes that the registration process could have induced. The amplitude of the derivatives increased with registration (Figure 3). RMS values of these changes are presented in Table 2: RMS values of the 1st derivative were smaller for muscle moment and larger for angular displacement. For the 2nd derivative, the minimum and maximum values were again found for the moment data and angular displacement.

With a gait cycle normalized to 100%, means and medians of the spectra were expressed in number of harmonics. As shown in Table 3 for both unregistered and registered data, mean number of harmonics is lower for angular displacement and higher for muscle power with corresponding lower or higher SD. Statistical difference between the two conditions was only found for the muscle moment; following the registration process. For angular displacement a non-significant decrease was observed while for the muscle power a small increase is present.

Table 2:RMS values between the mean curves and their corresponding unregistered and registered individual curves for sixty trials developed at the hip in the sagittal plane during gait of young able-bodied subjects. Differences for the 1st and 2nd derivatives for the unregistered and registered data are also presented.

Parameter	RMS								
	Unregistered	Registered	Diff (%)	First derivative (W/kg/step)			Second derivative (W/kg/step^2)		
	Mean (SD)	Mean (SD)		Unregistered	Registered	Diff. (%)	Unregistered	Registered	Diff. (%)
Angular displacement	1.23 (0.69)	0.79 (0.45)	56.0*	158.41	162.26	2.4	1619.08	1781.17	10.0
Muscle moment	0.02 (0.01)	0.02 (0.01)	0.0	3.30	2.57	22.3	137.07	34.02	75.2*
Muscle power	0.06 (0.03)	0.05 (0.03)	20.0	8.87	9.71	9.5	178.45	200.94	12.6

Statistically significant differences ($p<0.05$) are indicated by *.

Table 3: Mean and median frequency (with SD) of the power spectrum (expressed in number of harmonics) for the unregistered and registered hip data obtained from all trials of each of the 20 subjects.

Parameter	**Unregistered**		Registered	
	Mean (SD)	Median (SD)	Mean (SD)	Median (SD)
Angular displacement	1.08 (0.14)	1.54 (0.13)	1.06 (0.16)	1.52 (0.15)
Muscle moment	1.32 (0.29)*	1.50 (0.19)*	1.00 (0.19)*	1.38 (0.16)*
Muscle power	2.54 (0.38)	2.91 (0.48)	2.55 (0.38)	2.94 (0.45)

Statistically significant differences ($p<0.05$) are indicated by *.

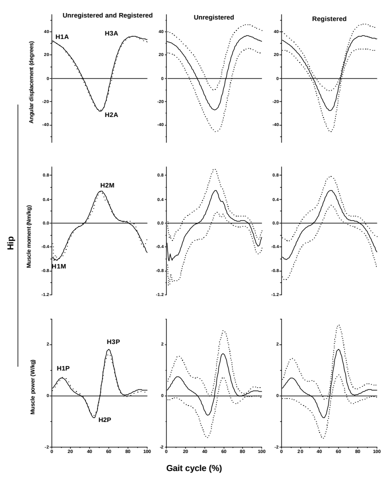

Figure 2. Mean and standard deviation of the unregistered (center) and registered (right). At the left, mean unregistered (solid line) and registered curves (thin lines) are superimposed.

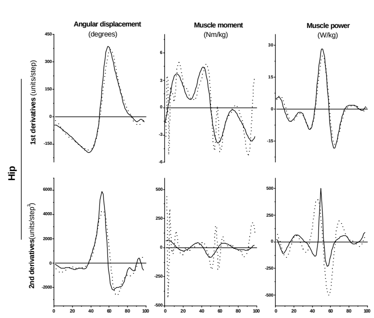

Figure 3. First and second derivative of the angular displacement, muscle moments and power curves for unregistered (dotted lines) and registered (solid lines) developed at the hip sagittal plane during gait cycle.

V. DISCUSSION

The objective of this study was to demonstrate how continuous curve registration can reduce inter-subject variability by normalizing time-related events occurring during the gait cycle. The main advantage of the continuous approach over the marker curve registration is that it can be applied not only when the curves differ from each other in the time domain by a constant time shift, but also to the case that curves differ from each other in the time domain by variable time shift and scaling factor. Continuous curve registration, provide better result if the data the data meet at least two criteria [7]. First, all curves should have a typical structural pattern common to all samples derived from different subjects, notwithstanding variations in both amplitude and phase between individual curves. This is an important consideration. Using multivariate analysis in able-bodied gait analysis, Vardaxis et al. [11] have shown that subjects display a high similarity between their own gait trials. However, this requirement may not be fulfilled when assessing other populations. For example, Watelain et al. [12] used cluster analysis to group gait trials of young able-bodied and healthy elderly subjects.

Discrepancies were found between the gait trials of the elderly subjects. This was attributed to the difficulty obtaining reproducible gait trials particularly for the phasic and temporal gait parameters as well as for the sagittal muscle powers. Nonetheless, in certain gait pathologies such as cerebral palsy, variations in consecutive gait trials can make these data unsuitable for curve registration. It is thus recommended that the mean registered curve obtained from able-bodied subjects be used as a reference to compare any able-bodied gait patterns. For pathological gait where the same labeling points as in able-bodied gait patterns can be recognized, curve registration techniques may be suitable.

The second criterion requires to gain better result is if the landmarks chosen for curve alignment are clearly visible and identifiable in all individual curves. These landmarks are relatively easy to identify in the sagittal plane data where peak values are high and zero-crossing well defined. Landmarks are more easily determined in able-bodied subjects than in some pathological gait patterns. For subjects with a total hip replacement prosthesis [13], peak muscle powers were not well defined which may impede the registration of the data. Nonetheless, clear peak power bursts were reported in below-knee amputees for all planes [14].

Also, Olney et al. [15] reported muscle power curves in hemiplegic patients which displayed a similar pattern allowing for identification of power bursts.

The major impact of applying continuous curve registration to able-bodied gait data is to provide a better representative mean curve where peak values have been aligned. These peak values taken from the registered curves correspond to the mean peaks calculated from the individual values taken on the unregistered curves. The registration technique is not intended to change the peak values of individual trials. Changes in the mean curve occur because the peak values do not occur at the same time. This technique would be appropriate when similar curves from different subjects are to be averaged.

Following small shifts in the timing of the peaks, inflection points and zero-crossings by the registration process, the curve structural characteristics were not greatly modified. These is evidenced by the absence of any discontinuity in their first and second derivatives and by only small changes in the median or mean harmonics of their power spectra. However, the RMS values of the derivatives of the registered curves were larger than for the unregistered ones. This may be associated with the restoration of some of the characteristics of the original signals which were smoothed out when the curves with unsynchronized peaks were grouped. While no suspect distortions in the registered curves were detected visually, no formal evaluation of this aspect was done. Consequently, part of the increase may also be associated with this factor. Like other types of normalization methods, the registration technique reduced inter-subject variability but did not remove the inherent variability which exists between individual gait patterns. This is particularly important since push-off is closely associated with walking speed [16] and these values are often used to compare pathological performances with able-bodied gait.

Considering that curve registration has a tendency to slightly increase the peak powers and reduce the variability without substantially affecting the curve structural characteristics, it is recommended that curve registration be performed on able-bodied gait data prior to further statistical analyses. By reducing the standard deviations in able-bodied gait parameters, the registration process would have a tendency to increase the probability of finding significant differences.

V. CONCLUSION

Curve registration was responsible for a slight increase in peak muscle powers and a reduction in the variability of the muscle power curves. The mean increase was 1.2% for angular displacement and 11.2 for muscle power in able-bodied sampled population. There was a 25% average decrease in the RMS value of the mean registered curves compared to the mean unregistered data. Reductions were generally observed in the sagittal plane. No important discontinuities were reported in the first and second derivatives of the registered curves. Harmonic content of the power spectrum was not affected significantly. Curve registration is thus recommended prior to any gait pattern analysis of able-bodied subjects.

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